Neutrino Clustering in Dark Matter Halos and the Nonlinear Cosmological Matter Power Spectrum

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The detection of neutrino flavor oscillation in conjunction with cosmological arguments have highly constrained neutrino masses. Solar neutrinos and atmospheric neutrinos oscillate from one flavor to another. The KamLAND reactor neutrino detector has found evidence for neutrino oscillations consistent with the inferred solar neutrino oscillation parameters; and the K2K long-baseline experiment has found evidence for neutrino oscillations consistent with the atmospheric results. While flavor oscillation experiments constrain only the neutrino mass differences, cosmological arguments have the advantage of constraining the total mass. The present cosmological upper limits are competitive with terrestrial experiments and expected to improve substantially with time.

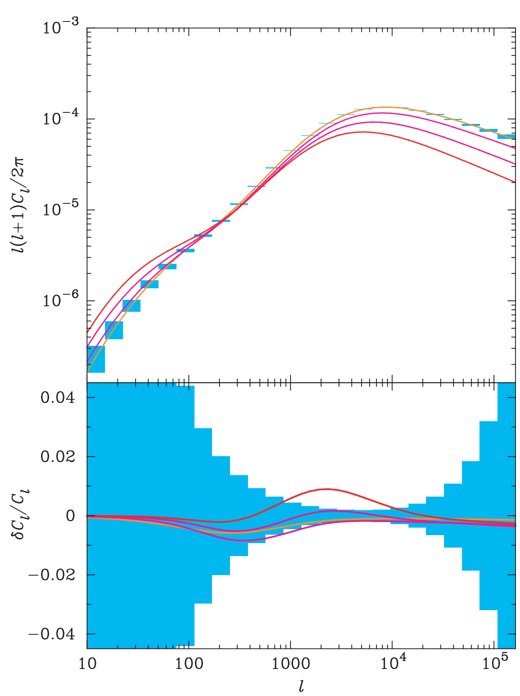

Figure 1— ***The weak lensing convergence power spectrum (upper panel) in the halo model for nonzero neutrino mass models of 0.1 eV, 0.3 eV, 0.6 eV, and 0.9 eV, with decreasing peak convergence, respectively. The power spectra are normalized at σ_8= 0.9, therefore showing a pivot at l~200. The deviations including and excluding this effect are plotted in the lower panel, with increasing mass neutrinos corresponding to an increased amplitude of the effect. Cyan boxes are expected errors for an LSST-like survey.***

Massive neutrinos influence the large-scale structures of the universe in a well-defined way because they do not cluster, thereby reducing the amount of matter that can accrete into potential wells. The galaxy power spectrum has been measured on large scales leading to upper limits on the sum of neutrino mass ranging from 0.7 to 1.8 eV (depending on assumptions and data sets). The approximation of a linear spectrum valid for such large-scale measurements breaks down on smaller scales where matter is highly clustered. Therefore, all studies (except for [1]) use data on the largest scales.

Using small-scale data in galaxy surveys requires knowing the nonlinear clustering and bias of galaxies relative to the dark matter. When large weak lensing surveys—which measure the mass distribution directly—become available, it will be essential to make direct use of this information, even on the smallest scales due to the expected precision of their results. We use an analytic Boltzmann solution of neutrino infall into cold dark matter (CDM) halos to calculate the modification of the halo profile due to captured neutrinos on the halos. We then employ the halo model to calculate matter-clustering statistics including the effects of neutrino clustering, as well as the modification of the weak lensing power spectrum while including or ignoring this effect. We also employ multiple particle (neutrino plus CDM) N-body simulations to estimate effects from neutrino clustering the nonlinear matter power spectrum, and study the ability of the Boltzmann solution with the halo model to accurately characterize the modification of the halo profile and dark matter statistics.

The potential precision of planned weak lensing surveys to measure the matter power spectrum is promising [2]. Therefore, in [3] we calculate the deviations due to massive neutrino clustering on a weak lensing observable, namely the convergence power spectrum, C_l. This quantity is effectively the projected angular matter-matter power spectrum weighted by the distribution of lensed galaxies. The modification of the expected weak lensing signal in the halo model due to neutrino clustering is shown in Fig. 1.

We also perform N-body simulations of nonlinear matter clustering in universes with massive neutrinos to find the deviation of the matter power spectrum. We use the N-body solvers Meshed-based Cosmology Code (MC^2) developed at Los Alamos National Laboratory (LANL) and University of California at Los Angeles, and the Hashed-Oct Tree (HOT) Code also developed at LANL to solve multiple-particle dark matter clustering. Representative results from an MC^2 neutrinos+CDM run are shown in Fig. 2.

In general cases where massive neutrinos are present in fits to observed weak lensing convergence power spectra, massive neutrinos will need to be included in N-body simulation predictions of the weak lensing signal in addition to phenomena arising from baryonic condensation and heating, leading to the necessity of high-resolution multiparticle (neutrino, CDM, and baryon) hydrodynamic N-body simulations. Coupled with upcoming weak lensing surveys, these predictions will be a powerful probe of the contents of the cosmological soup as well as the process of cosmological structure formation.

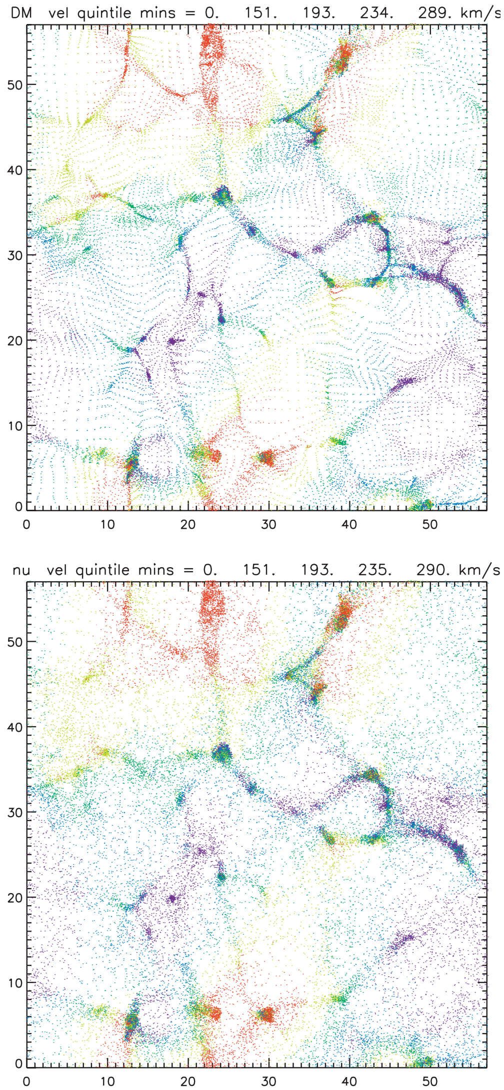

Figure 2—***Distribution of cold dark matter particles (top) and neutrinos (bottom) in a 1 h^{-1} Mpc slice of a 100 h^{-1} Mpc box at $z = 0$. While the velocities and large-scale distributions are similar, neutrinos are less clustered, as is apparent in the voids.***

[1] K. Abazajian et al., "Cosmology and the Halo Occupation Distribution from Small-Scale Galaxy Clustering in the Sloan Digital Sky Survey," Los Alamos National Laboratory report LA-UR-04-1126 (2004) [arXiv:astro-ph/0408003].
[2] K. Abazajian and S. Dodelson, "Neutrino Mass and Dark Energy from Weak Lensing," *Phys. Rev. Lett.* **91**, 041301 (2003) [arXiv:astro-ph/0212216].

[3] K. Abazajian, E. Switzer, S. Dodelson, K. Heitmann, and S. Habib, "The Nonlinear Cosmological Matter Power Spectrum with Massive Neutrinos," Los Alamos National Laboratory report LA-UR-04-7094 (2004) [astro-ph/0411552].